ANALYSIS OF TWO LEVEL AND THREE LEVEL INVERTERS

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF TECHNOLOGY IN "ELECTRICAL ENGINEERING"

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CERTIFICATE

This is to certify that the work in the project report entitled ***"Analysis of two level and three level inverters"*** by **Piyus Mohanty(10602010) and Saransh Sahoo(10602058)** has been carried out under my supervision in partial fulfillment of the requirement for the degree of Bachelor of Technology in **"Electrical Engineering**" during session 2008-09 in the **Department of Electrical Engineering, National Institute of Technology, Rourkela** and this work has not been submitted elsewhere for a degree.

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CONTENTS

ABSTRACT

The power electronics device which converts DC power to AC power at required output voltage and frequency level is known as inverter. Inverters can be broadly classified into single level inverter and multilevel inverter. Multilevel inverter as compared to single level inverters have advantages like minimum harmonic distortion, reduced EMI/RFI generation and can operate on several voltage levels. A multi-stage inverter is being utilized for multipurpose applications, such as active power filters, static var compensators and machine drives for sinusoidal and trapezoidal current applications. The drawbacks are the isolated power supplies required for each one of the stages of the multiconverter and it's also lot harder to build, more expensive, harder to control in software.

This project aims at the simulation study of three phase single level and multilevel inverters . The role of inverters in active power filter for harmonic filtering is studied and simulated in MATLAB/SIMULINK. Firstly, the three phase system with non-linear loads are modeled and their characteristics is observed . Secondly, the active power filters are modeled with the inverters and suitable switching control strategies (PWM technique) to carry out harmonic elimination .

CHAPTER #1

INTRODUCTION

When ac loads are fed through inverters it required that the output voltage of desired magnitude and frequency be achieved. A variable output voltage can b obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by pulse-width-modulation (PWM) control within the inverter.

The inverters which produce which produce an output voltage or a current with levels either 0 or +-V are known as two level inverters. In high-power and high-voltage applications these two-level inverters however have some limitations in operating at high frequency mainly due to switching losses and constraints of device rating. This is where multilevel inverters are advantageous. Increasing the number of voltage levels in the inverter without requiring higher rating on individual devices can increase power rating. The unique structure of multilevel voltage source inverters' allows them to reach high voltages with low harmonics without the use of transformers or series-connected synchronized-switching devices. The harmonic content of the output voltage waveform decreases significantly.

1.1 PROJECT OUTLINE

- Study of two level and three level inverters
- Simulation of three phase voltage source inverter
- Modeling of a three phase system with non-linear loads
- Collecting information about simulation work and requisite theory / formulae
- Simulation of the multilevel inverter, study of the obtained simulated results and analysis(THD factor , FFT analysis)
- Application of the inverters (2 level and 3 level). Modeling of the circuits and harmonic elimination by use of inverters in active power filters

1.2 INVERTER

A dc-to-ac converter whose output is of desired output voltage and frequency is called an inverter.

Based on their operation the inverters can be broadly classified into

- Voltage Source Inverters(VSI)
- Current Source Inverters(CSI)

A voltage source inverter is one where the independently controlled ac output is a voltage waveform.
A current source inverter is one where the independently controlled ac output is a current waveform.

On the basis of connections of semiconductor devices, inverters are classified as

- Bridge inverters
- Series inverters
- Parallel inverters

Some industrial applications of inverters are for adjustable- speed ac drives, induction heating, stand by air-craft power supplies, UPS(uninterruptible power supplies) for computers, hvdc transmission lines etc.

CHAPTER #2

PULSE MODULATION SCHEMES

2.1 PULSE AMPLITUDE MODULATION

Pulse Amplitude Modulation refers to a method of carrying information on a train of pulses, the information being encoded in the amplitude of pulses. In other words the pulse amplitude is modulated according to the varying amplitude of analog signal.

2.2 PULSE WIDTH MODULATION

Pulse Width Modulation refers to a method of carrying information on a train of pulses, the information being encoded in the width of the pulses. The pulses have constant amplitude but their duration varies in direct proportion to the amplitude of analog signal.

2.3 PULSE POSITION MODULATION

The amplitude and width of the pulse is kept constant in the system. The position of each pulse, in relation to the position of a recurrent reference pulse, is varied by each instantaneous sampled value of the modulating wave. PPM has the advantage of requiring constant transmitter power since the pulses are of constant amplitude and duration.

2.4 PULSE CODE MODULATION

To obtain PCM from an analog waveform at the source (transmitter), the analog signal amplitude is sampled at regular time intervals. The sampling rate (number of samples per second), is several times the maximum frequency of the analog waveform. The amplitude of the analog signal at each sample is rounded off to the nearest binary level (quantization). The

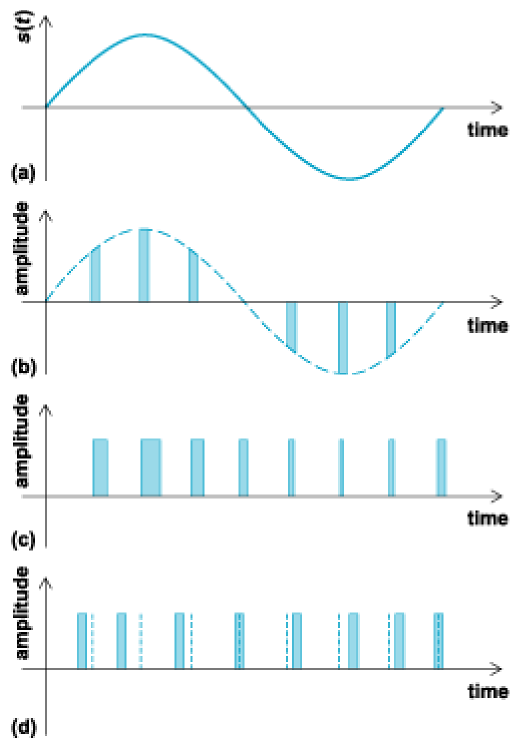


Figure 1*(a)* Analog signal, *s*(*t*). (*b*) Pulse-amplitude modulation. (*c*) Pulse-width modulation. (*d*) Pulse position modulation

Number of levels is always a power of 2 (4, 8, 16, 32, 64, ...). These numbers can be represented by two, three, four, five, six or more binary digits.

PCM is a general scheme for transmitting analog data in a digital and binary way, independent of the complexity of the analog waveform. With PCM all forms of analog data like video, voice, music and telemetry can be transferred.

2.6 ADVANTAGES OF PWM

- The output voltage control is easier with PWM than other schemes and can be achieved without any additional components.
- The lower order harmonics are either minimized or eliminated altogether.
- The filtering requirements are minimized as lower order harmonics are eliminated and higher order harmonics are filtered easily.
- It has very low power consumption.
- The entire control circuit can be digitized which reduces the susceptibility of the circuit to interference.

CHAPTER #3

PULSE WIDTH MODULATION

PWM is the most popular method for producing a controlled output for inverters. They are quite popular in industrial applications.

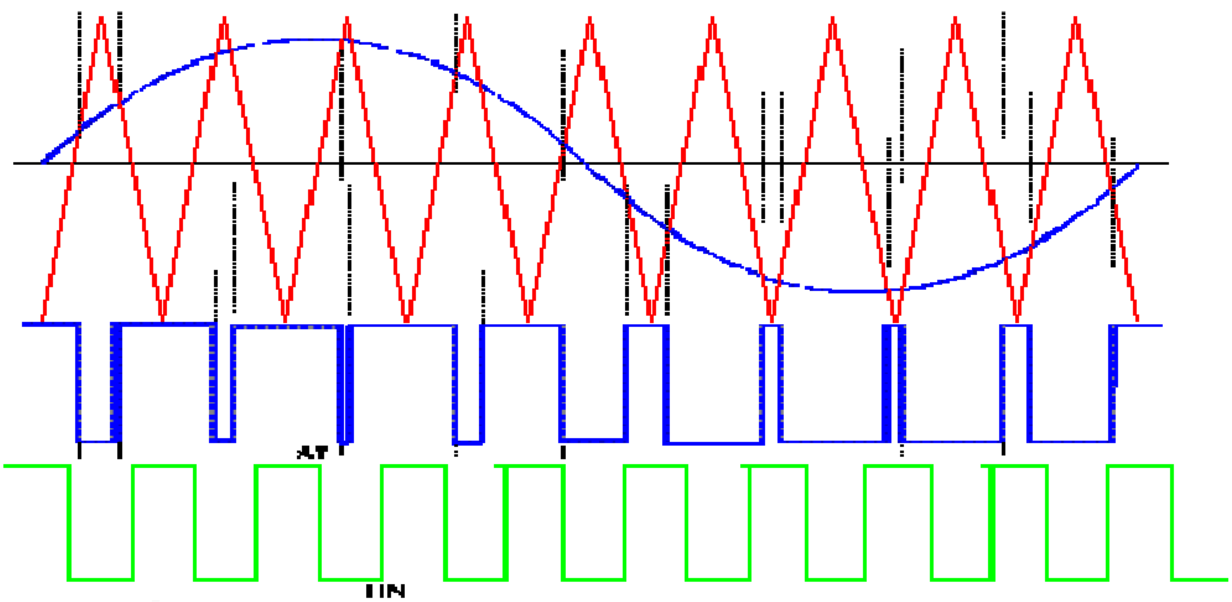


Figure2 (sine modulated, unmodulated signal)

3.1 LINEAR MODULATION

The simplest method is to vary the ON time proportionally with the modulating signal. Its advantage is that it is easy to demodulate. The modulating or information signal can be recovered by low pass filtering. A low frequency (fm) sine wave modulating the width of a fixed frequency (fs) pulse train is shown in the figure 3. As can be seen a low pass filter can extract the modulating signal (fm).

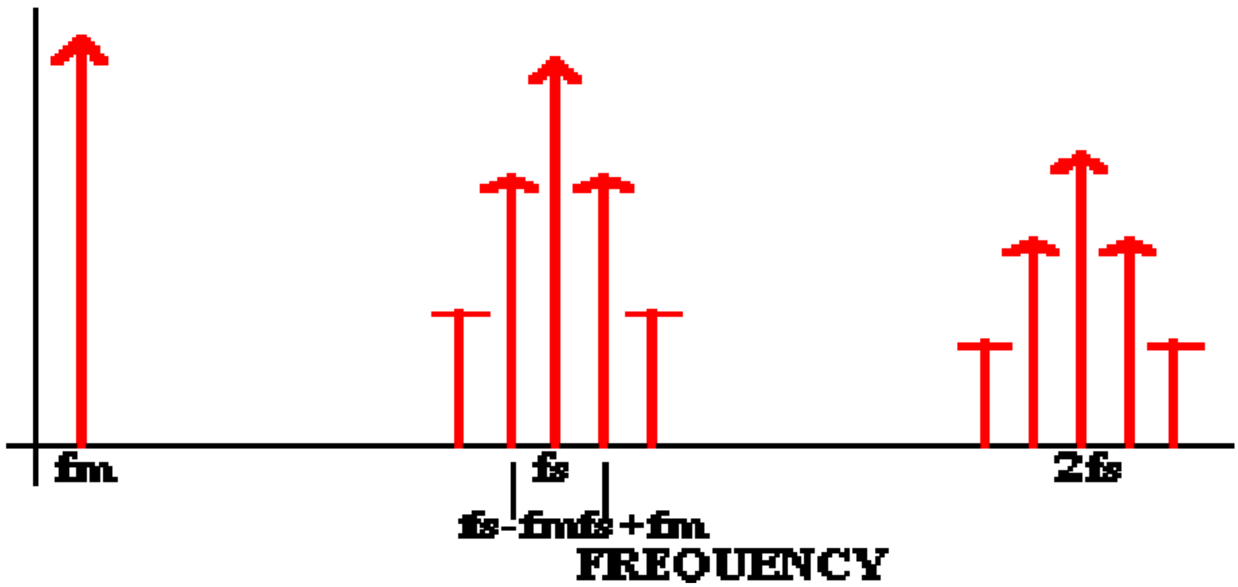
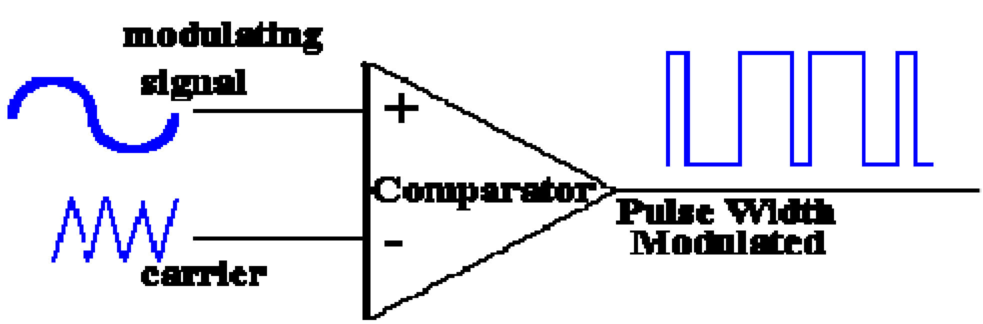


Figure 3.

3.2 SAW TOOTH PWM

A fixed frequency PWM can be generated by comparing with a linear slope waveform like a saw tooth waveform. As seen in the figure the output goes high when the sine wave amplitude is greater than saw tooth. It can be achieved by comparator with logic HIGH when non-inverting input is greater than the inverting one.



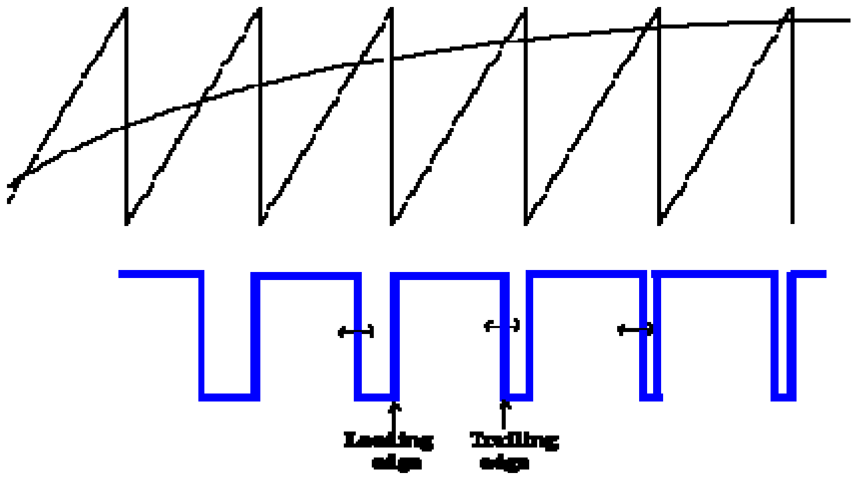


Figure 4.1 & 4.2

3.3 REGULAR SAMPLED PWM

This scheme works by generating a switching edge at the intercept of carrier and modulating signal. In the figure 5 intercepts of sampled sine values with the triangular wave gives the edges of the pulses.

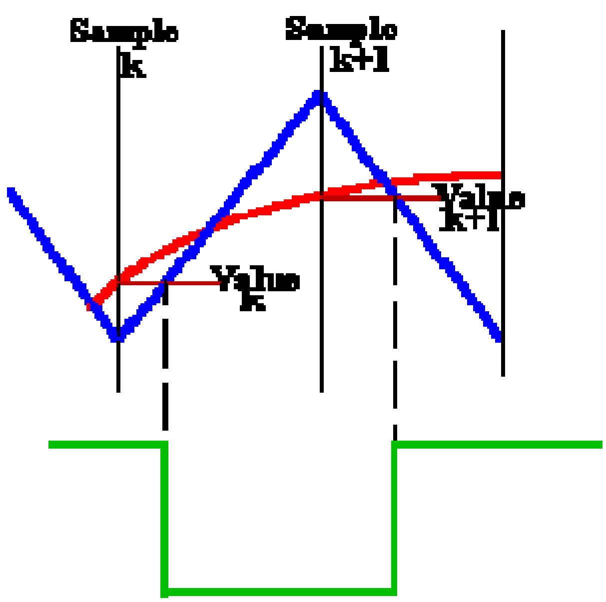


Figure 5(Regular sampled PWM)

SINGLE PHASE PWM INVERTERS

In many industrial applications, to control the output voltage of the inverters is necessary for the following reasons

- To adjust with variations of dc input voltage
- To regulate voltage of inverters
- To satisfy the contain volts and frequency control requirement

There are various techniques to vary the inverter gain. The most efficient method of Controlling the gain (and output voltage) is to incorporate pulse width modulation (PWM) Control within the inverters. The commonly used techniques are

a) Single Pulse width Modulation
b) Multiple Pulse width Modulation
c) Sinusoidal Pulse width Modulation
d) Modified sinusoidal Pulse width Modulation
e) Phase-displacement control.

The PWM techniques given above vary with respect to the harmonic content in their output voltages.

4.1 SINGLE PULSE WIDTH MODULATION

In this control, there's only one pulse per half cycle and the width of the pulse is varied to control the inverter output. The gating signals are generated by comparing a rectangular reference signal of the amplitude A_r with triangular carrier wave of amplitude A_c, the frequency of the carrier wave determines the fundamental frequency of output voltage. By varying A_r from 0 to A_c ,the pulse width can be varied from 0 to 100 percent. The ratio of A_r to A_c is the control variable and defined as the modulation index.

4.2 MULTIPLE PULSE WIDTH MODULATION

The harmonic content can be reduced by using several pulses in each half cycle of output voltage. The generation of gating signals for turning ON and OFF transistors by comparing a reference signal with a triangular carrier wave. The frequency F_c, determines the number of pulses per half cycle. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse width modulation (UPWM).

4.3 SINUSOIDAL PULSE WIDTH MODULATION

Instead of, maintaining the width of all pulses of same as in case of multiple pulse width modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The distortion factor and lower order harmonics are reduced significantly. The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency F_c. The frequency of reference signal F_r ,determines the inverter output frequency and its peak amplitude A_r, controls the modulation index M, and rms output voltage Vo. The number of pulses per half cycle depends on carrier frequency .

PWM STRATEGIES WITH DIFFERING PHASE RELATIONSHIPS

We have used the intersection of a sine wave with a triangular wave to generate firing pulses. There are three alternative strategies to to implement this. They are as given below.

1) Alternate phase disposition (APOD) – every carrier waveform is in out of phase with its neighbor carrier by 180.

2) Phase opposition disposition (POD) – All carrier waveforms above zero reference are in phase and are 180 degree out of phase with those below zero

2) Phase disposition (PD)- All carrier waveforms are in phase

5.1 ALTERNATE PHASE DISPOSITION (APOD)

As can be seen in the figure for a three level inverter a total of four carrier waves are used.

1)They are arranged in such a manner that each carrier is out of phase with its neighbor by 180 degrees.

2)The converter switches to + Vdc / 2 when the sine wave is higher than all carrier waveforms

3)The converter switches to Vdc / 4 when the sine wave is lower than the uppermost carrier waveform and greater than all other carriers

4) The converter switches to 0 when the sine wave is lower than the two uppermost carrier waveform and greater than two lowermost carriers

5) The converter switches to - Vdc / 4 when the sine wave is higher than the lowermost carrier waveform and lesser than all other carriers.

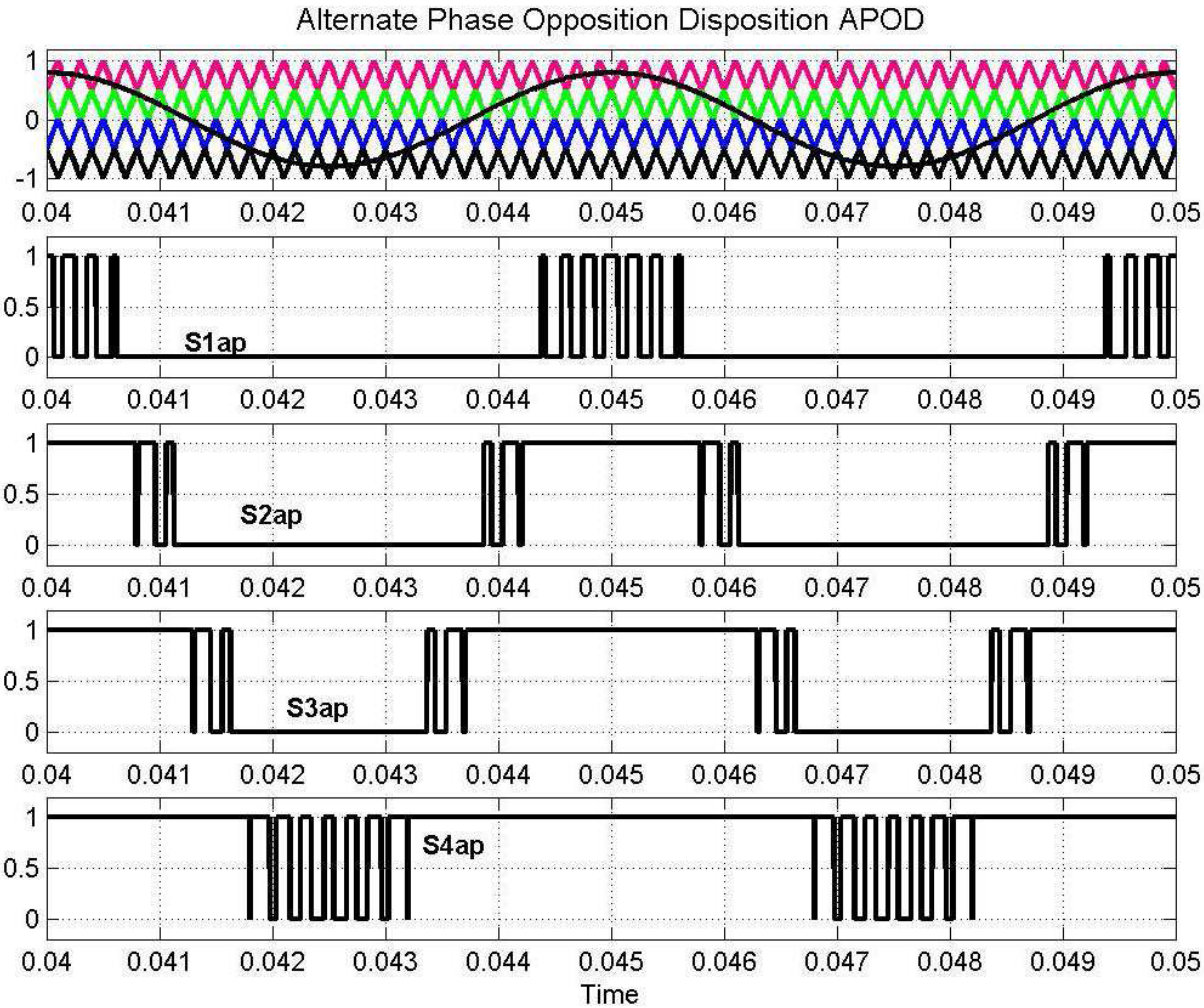


Figure 6 (Switching pattern produced using the APOD carrier-based PWM scheme for a three-level inverter: (a) Four triangles and the modulation signal (b) S1ap (c) S2ap (d) S3ap (e) S4ap.

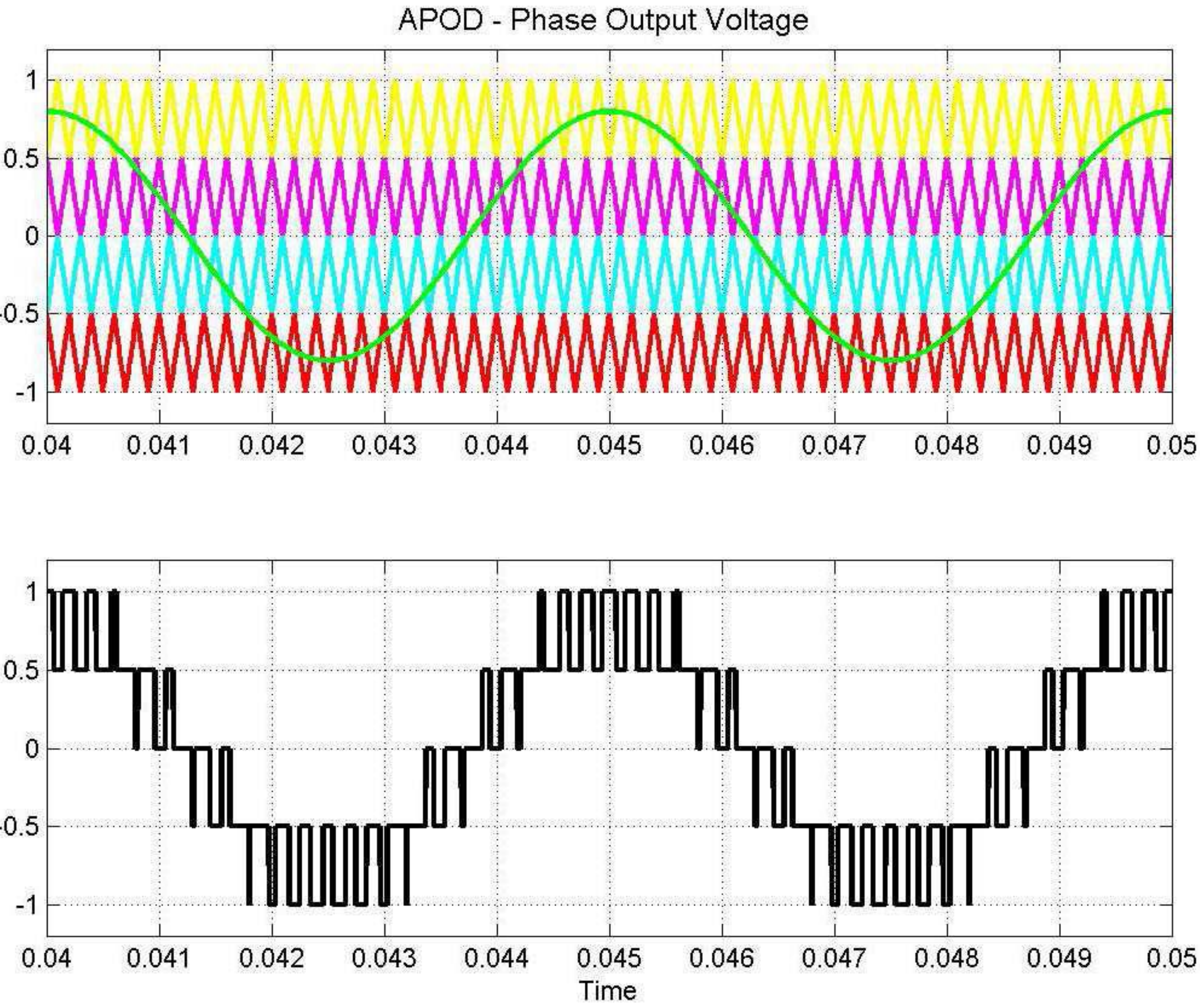


Figure 7.(Simulation of carrier-based PWM scheme using APOD for a three-level inverter. I. Modulation signal and carrier waveforms (II) Phase “a” output voltage.)

Figure . Demonstrates the APOD scheme for a three-level inverter. The figure displays the switching pattern generated by the comparison of the modulation signals with the four carrier waveforms. Figure 9 Shows the output voltage waveform of phase “a” and it is clear the waveform has five steps.

5.2 PHASE OPPOSITION DISPOSITION (POD)

The rules for the two level inverter

1) Two carrier waveforms are arranged so that all carrier waveforms above zero are in phase and are 180 degrees out of phase with those below zero

2) The converter is switched to + Vdc / 2 when the sine wave is higher than both carrier waveforms

3) The converter is switched to zero when the sine wave is greater than the lower carrier waveform but less than the upper carrier waveform

4) The converter is switched to - Vdc / 2 when the sine wave is less than both carrier waveforms

As seen from Figure, the figure illustrates the switching functions produced by POD carrier based PWM scheme. In the PWM scheme there are two triangles, upper triangle magnitude from 1 to 0 and the lower triangle from 0 to –1 and these two triangle waveforms are in out of phase.

When the modulation signal is greater than both the carrier waveforms, S1ap and S2ap are turned on and the converter switches to positive node voltage and when the reference is less than the upper carrier waveform but greater than the lower carrier, S2ap and S1an are turned on and the converter switches to neutral point. When the reference is lower than both carrier waveforms, S1an and S2an are turned on and the converter switches to negative node voltage.

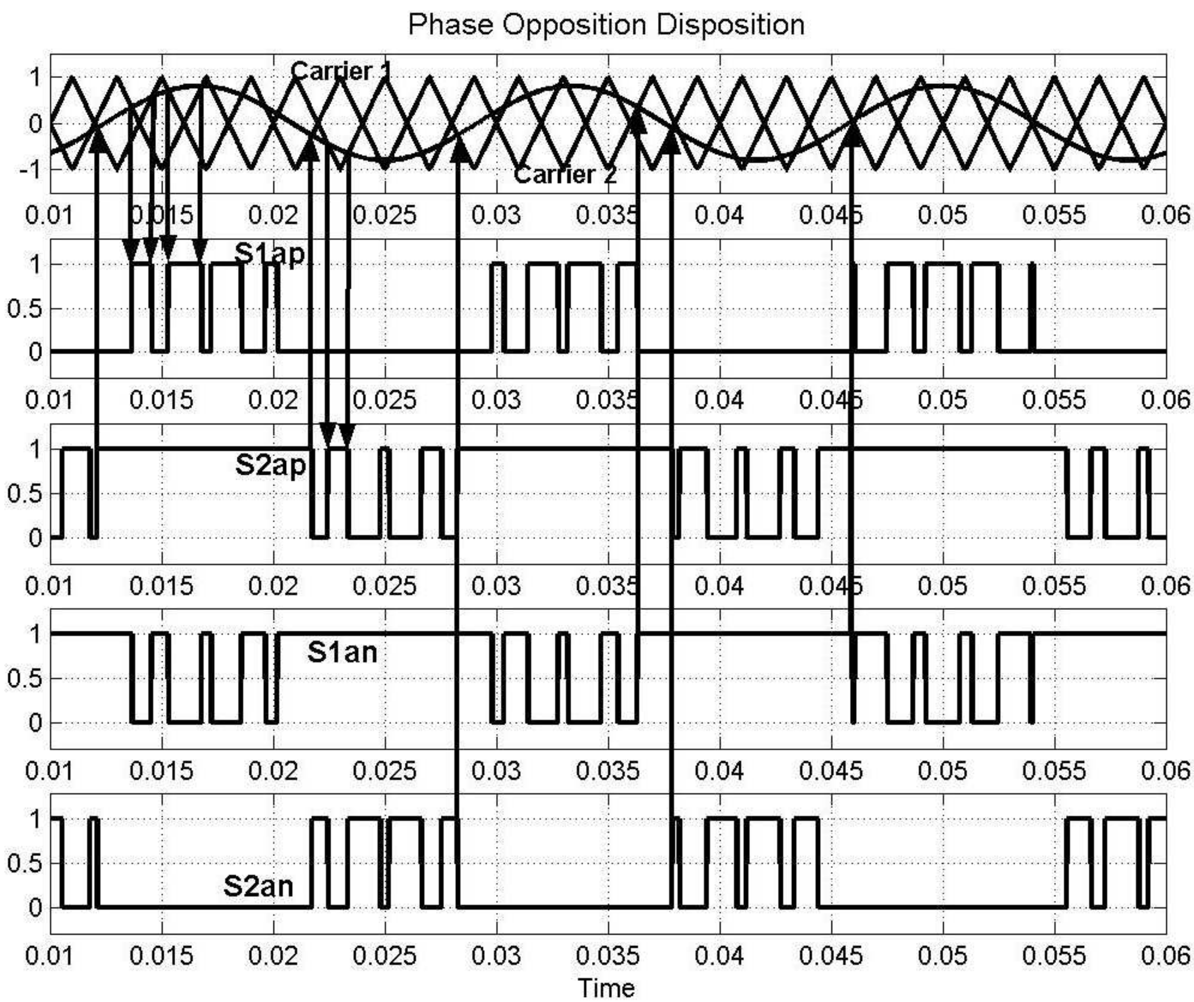


Figure 8.(Switching pattern produced using the POD carrier-based PWM scheme: (a) two triangles and the modulation signal (b) S1ap (c) S2ap (d) S1an (e) S2an

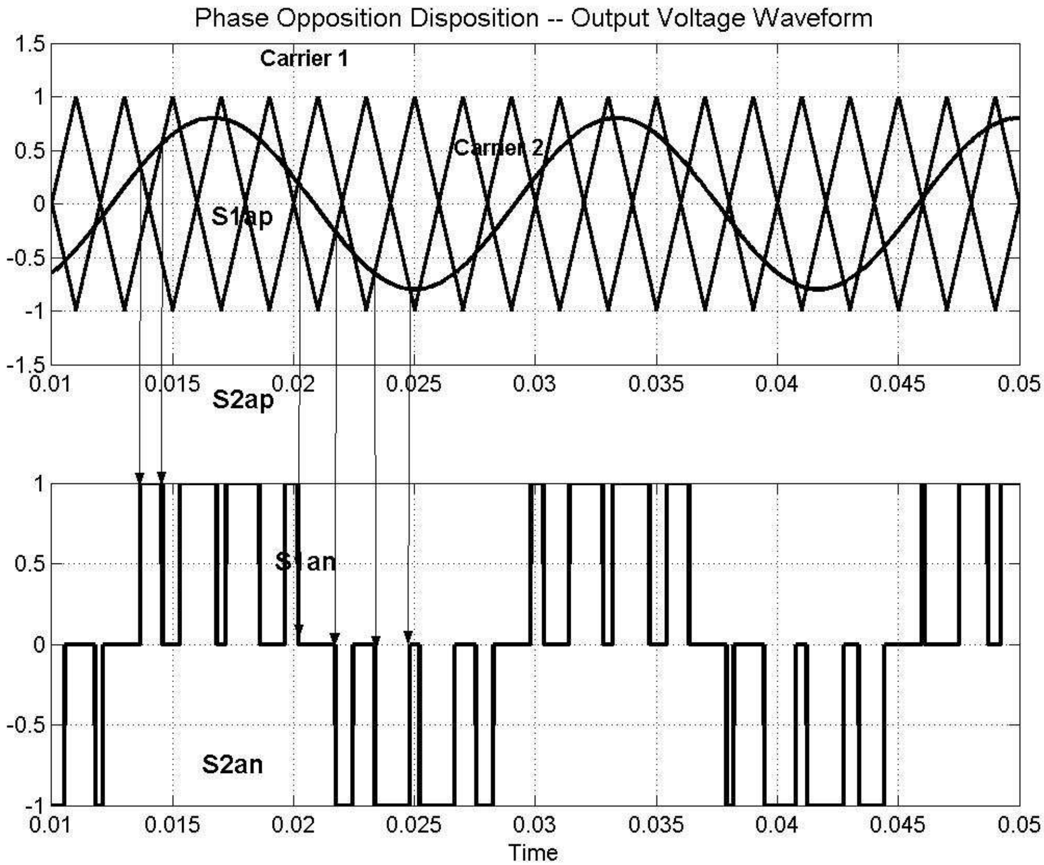


Figure 9.(Simulation of carrier-based PWM scheme using POD. I. Modulation signal and out of phase carrier waveforms (II) Phase “a” output voltage) Also shows the implementation of the phase disposition (PD) scheme. Shows the carriers waveforms are displaced out of phase and compared with the sinusoidal modulation signal. Figure . (II) Shows the phase “a” output voltage waveform.

5.3 PHASE DISPOSITION (PD)

The rules for phase disposition method for a two level inverter are

1) 2 carrier waveforms in phase are arranged.

2) The converter is switched to + Vdc / 2 when the sine wave is greater than both carrier waveform

3) The converter is switched to zero when sine wave is lower than upper carrier but higher than the lower carrier

4) The converter is switched to - Vdc / 2 when the sine wave is less than both carrier waveforms

As can be seen from the figure in the PWM scheme there are two triangles, the upper triangle ranges from 1 to 0 and the lower triangle ranges from 0 to –1. During the positive cycle of the modulation signal, when the modulation is greater than Triangle 1 and Triangle 2, then S1ap and S2ap are turned on and also during the positive cycle S2ap is completely turned on. When S1ap and S2ap are turned on the converter switches to the + Vdc / 2 and when S1an and S2ap are on, the converter switches to zero and hence during the positive cycle S2ap is completely turned on and S1ap and S1an will be turning on and off and hence the converter switches from + Vdc / 2 to 0. During the negative half cycle of the modulation signal the converter switches from 0 to -Vdc / 2.

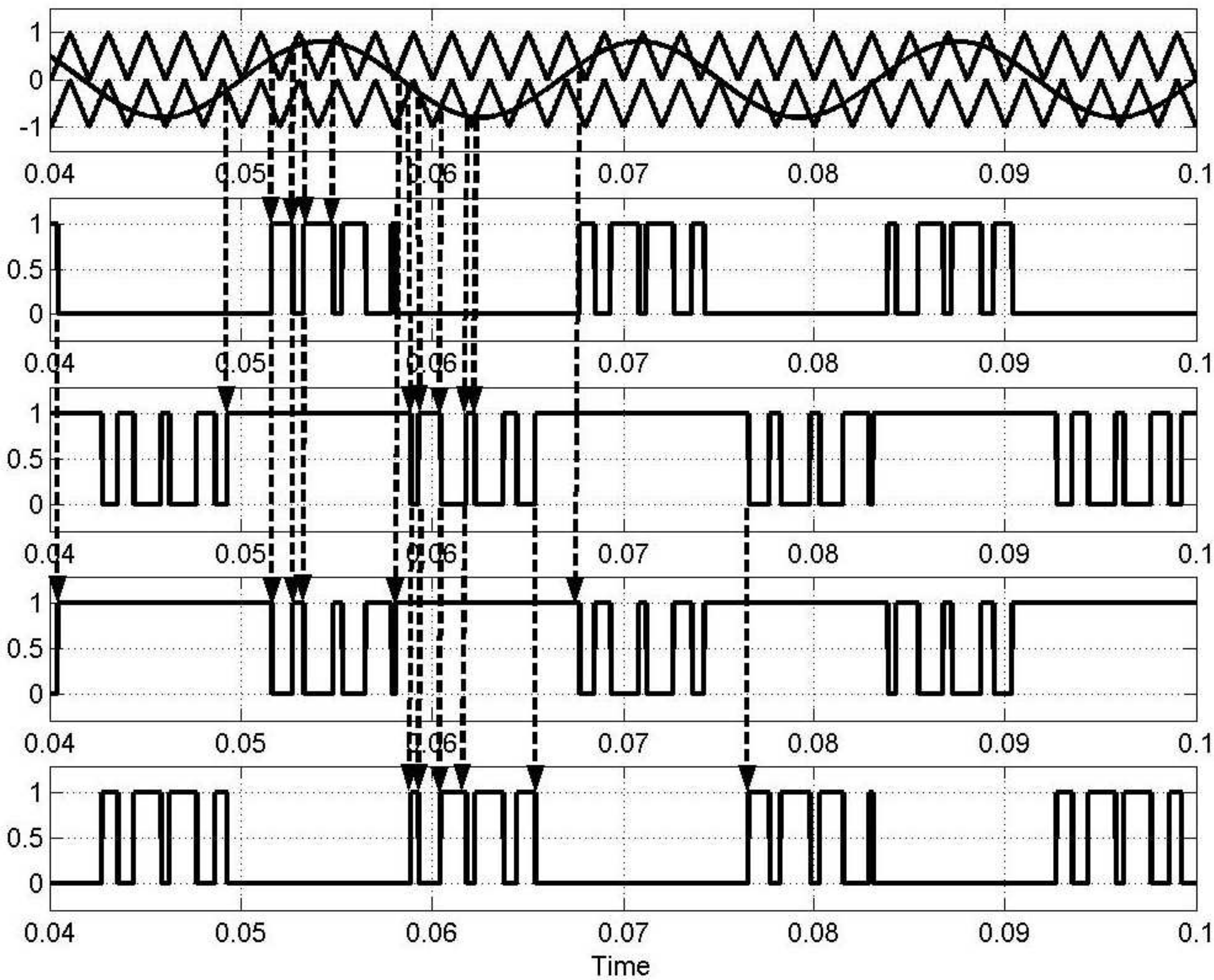


Figure 10(Switching pattern produced using the PD carrier-based PWM scheme: (a) two triangles and the modulation signal (b) S1ap (c) S2ap (d) S1an (e) S2an.)

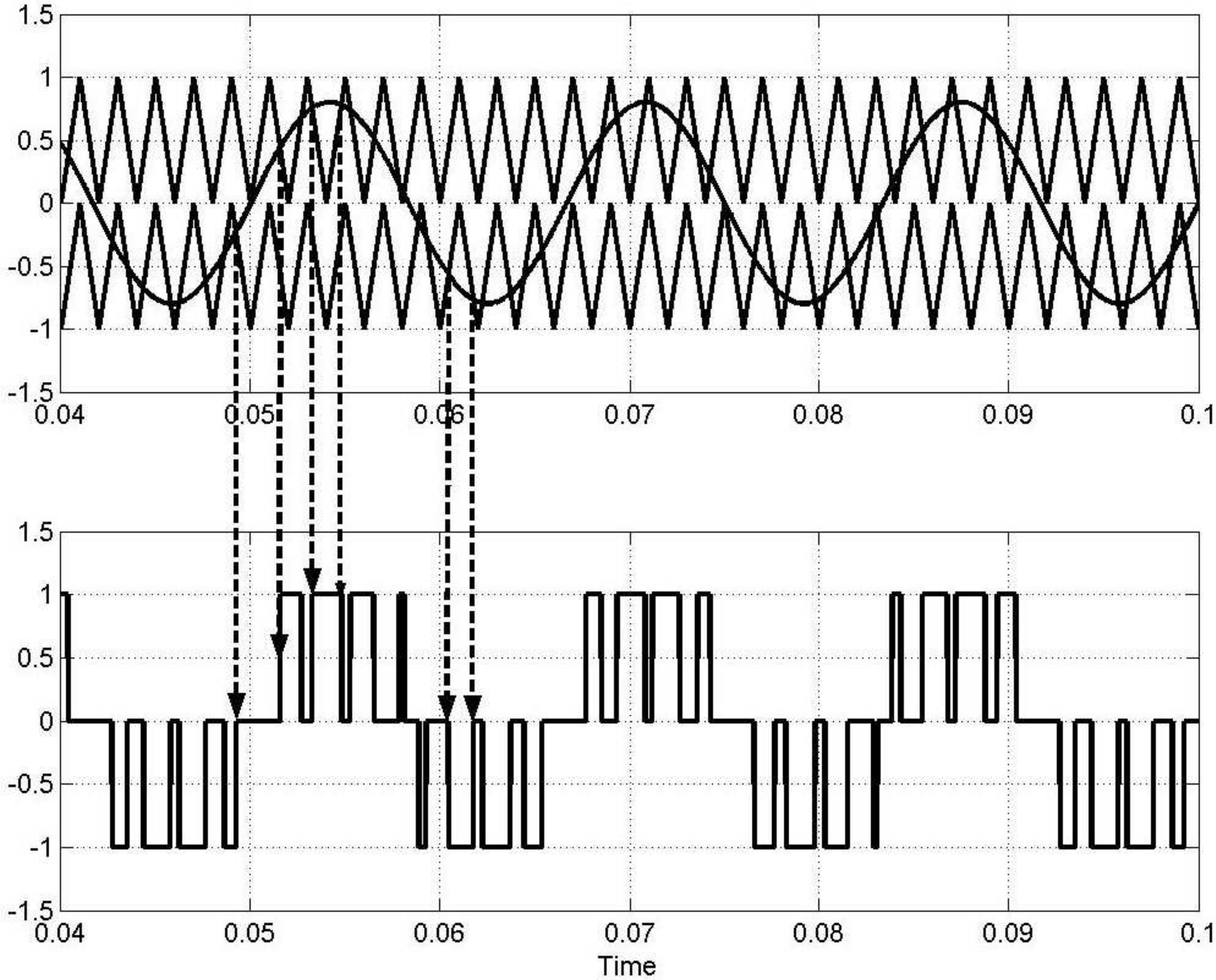


Figure 11(Simulation of carrier-based PWM scheme using the phase disposition (PD).
I. Modulation signal and in-phase carrier waveforms (II) Phase “a” output voltage.)
Figure . Shows the implementation of the phase disposition (PD) scheme.
Figure 13 (I)shows that two carriers waveforms are displaced in phase and compared with the sinusoidal modulation signal. Figure . (II) Shows the phase “a” output voltage waveform.

CHAPTER#6

APPLICATIONS IN HARMONIC ELIMINATION

The present chapter helps us to understand the effects of non-linear loads on the power system and the implementation of suitable devices to cancel out the harmonics. The use of inverters in active power filters has been emphasized and the simulated circuits and results have been described in particular.

6.1 NON LINEAR LOADS

A non-linear load on a power system is typically a rectifier or some kind of arc discharge device such as a fluorescent lamp, electric welding machine, or arc furnace in which current is not linearly related to the voltage. Because current in these systems is interrupted by a switching action, the current contains frequency components that are multiples of the power system frequency. This leads to distortion of the current waveform which in turn distorts the voltage waveform. Distortion power factor is a measure of how much the harmonic distortion of a load current decreases the average power transferred to the load.

6.2 ACTIVE POWER FILTERS

The increasing use of power electronics based loads (adjustable speed drives, switch mode power supplies, etc.) to improve system efficiency and controllability is increasing the concern for harmonic distortion levels in end use facilities and on the overall power system. The application of passive tuned filters creates new system resonances which are dependent on specific system conditions.

In general, passive tuned filters have been used to minimize low-frequency current harmonics while high-pass units have been connected to attenuate the amplitude of high frequency current components. However, high-pass filters present disadvantages due to the resistance connected in parallel to the inductor, which increases the filter losses and reduces the filtering effectiveness at the tuned frequency. The most critical aspects of passive filters are related to the fact that they cannot modify their compensation characteristics following the dynamic changes of the nonlinear load, the performance dependence they present with the power system parameters, and the probability of series resonances with the power system's equivalent reactance. Passive filter ratings must be coordinated with reactive power requirements of the loads and it is often difficult to design the filters to avoid leading power factor operation for some load conditions.

Also, the passive filter generates at fundamental frequency reactive power that changes the system voltage regulation, and if the filter is not designed properly or disconnected during low load operating conditions, over-voltages can be generated at its terminals.

A flexible and versatile solution to voltage/current quality problems is offered by active power filters. Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns. This means that the rating of the active power can be less than a conquerable passive filter for the same nonlinear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another.

Figure 6.2 shows the components of a typical active-power-filter system and their interconnections. The information regarding the harmonic current, generated by a nonlinear load, for example, is supplied to the reference-current/voltage estimator together with information about other system variables. The reference signal from the current estimator, as well as other signals, drives the overall system controller. This in turn provides the control for the PWM switching-pattern generator. The output of the PWM pattern generator controls the power circuit via a suitable interface. The power circuit in the generalized block diagram can be connected in parallel, series or parallel/series configurations, depending on the connection transformer used.

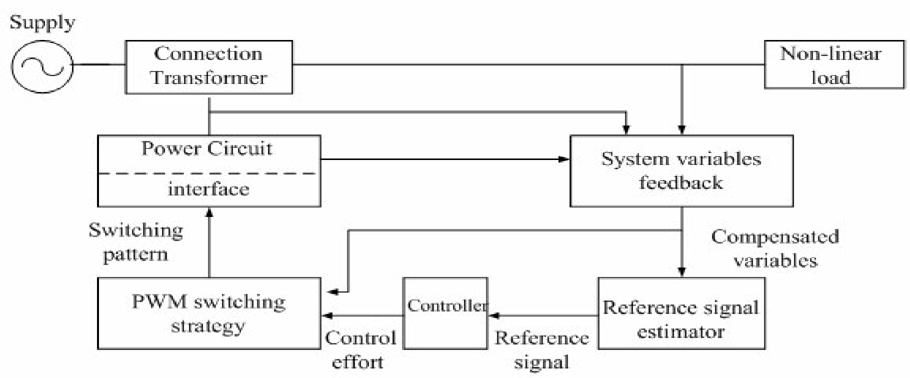


Fig. 6.2 Generalized block diagram for active power filters

6.3 SHUNT ACTIVE POWER FILTERS

The purpose of the shunt active power filters is to cancel load harmonics fed to the supply. It can also contribute to reactive-power compensation and balancing of three phase currents. Shunt active power filters compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this configuration active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180^{o}. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor.

Parallel filters have the advantage of carrying only the compensation current plus a small amount of active fundamental current supplied to compensate for system losses. It is possible to connect several filters in parallel to cater for higher currents, which makes this type of circuit suitable for a wide range of power ratings.

6.4 MODELLING OF THREE WIRE SHUNT ACTIVE POWER FILTER

The concept of using active power filters to mitigate harmonic problems and to compensate reactive power was proposed more than two decades ago [Akagi et al., 1984]. Since then the theories and applications of active power filters have become more popular and have attracted great attention. Without the drawbacks of passive harmonic filters, the active power filter appears to be a viable solution for reactive power compensation as well as for eliminating harmonic currents.

Active power filters are researched and developed as a viable alternative over the passive filters and static var compensators to solve the problems of harmonics injection and reactive power requirement of non-linear loads .Among the various topologies developed the shunt active power filter based on the current controlled voltage source type PWM converter has proved to be effective even when the load is highly non-linear.

The control strategies of the active filters are implemented mainly in three steps – Signal conditioning, estimation of compensating signals and generation of firing signals for switching devices. Estimation of compensating signal is the most important part of the active filter control. It has a great impact on the compensating objectives, rating of active filters and its transient as well as steady state performance. The control strategies use either frequency domain or time domain approaches to extract compensating signals from the corresponding distorted currents/voltages.

6.5 SYSTEM DESCRIPTION

The active power filter uses power electronic switching to generate harmonic currents that cancel the harmonic currents from a load. The active filter configuration investigated in this study is based on a voltage source inverter that interfaces to the system through an interface reactor. In this configuration, the filter is connected in parallel with the load being compensated. Therefore the configuration is often referred to as a shunt (parallel) active filter. The approach is based on the principle of injecting harmonic current into the AC system, of the same amplitude and reverse phase to that of the load current harmonics. Figure6.5 shows the main components of a typical active power filter system and their interconnections.

The main components of the system are :

(a) Mains supply (b) Non linear load (c) Active power filter

Active power filter – (i) voltage source inverter , (ii) interface reactor ,(iii) reference current generator , (iv) current controller .

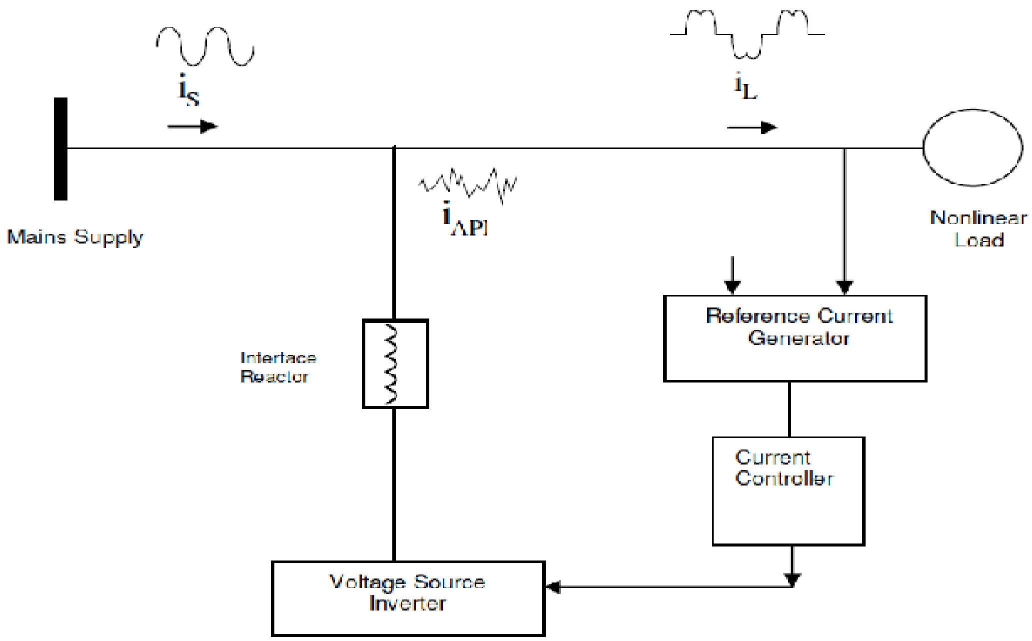


Fig.6.5 System model with shunt active power filter

6.6 MAINS SUPPLY

Mains supply is a three phase 415V 50 Hz wye connected power supply with a grounded neutral point equivalent of the actual system i.e. a three phase 3 wire system.

6.7 NON LINEAR LOAD

The nonlinear load block is a three-phase fully controlled bridge rectifier feeding a DC motor. The DC motor is modeled with a resistance, inductance and a back emf. It is possible to control the firing angle of the controlled three-phase rectifier. The Matlab/Simulink model of the nonlinear load block is shown in Figure 6.7(A).

Another non-linear load can be a three phase six-pulse converter feeding a RL load. This model of non-linear load has been used in the main model involving active power filters. The MATLAB/SIMULINK models of both kinds of non-linear loads are shown below in fig. 6.7(B)

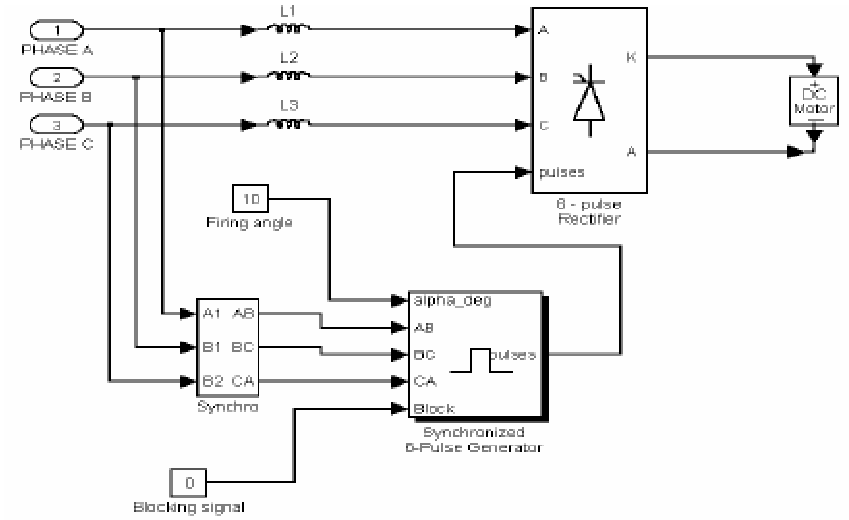


FIG.6.7(A) Simulink model of 3 phase controlled converter feeding DC motor as non-linear load

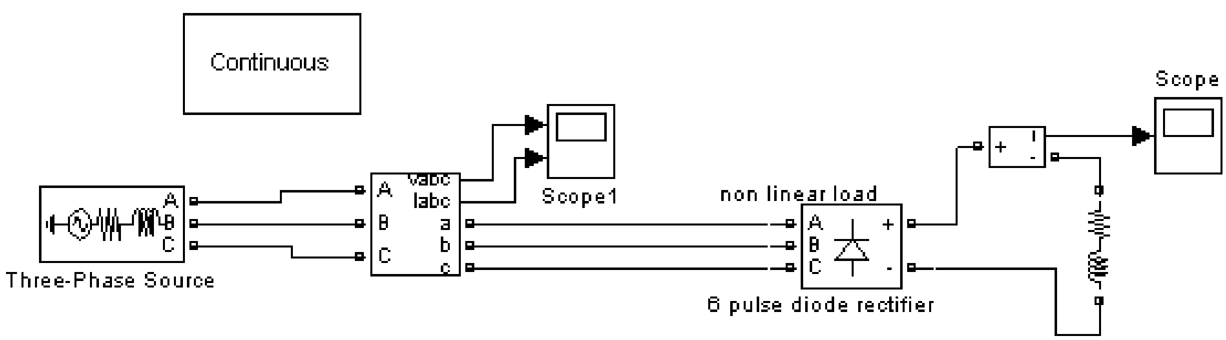


FIG 6.7(B) Simulink model of 6 pulse diode rectifier powering RL load as a non-linear load.

6.8 ROLE OF INVERTERS IN ACTIVE FILTERS

The voltage source inverter used in the active power filter makes the harmonic control possible. This inverter uses a dc capacitor as the supply and can switch at a high frequency to generate a signal which will cancel the harmonics from the nonlinear load.

The current waveform for cancelling harmonics is achieved with the voltage source inverter(IGBT based) and an interface reactor.The interface reactor converts the voltage signal created by the inverter to a current signal.The desired waveform is obtained by accurately controlling the switches in the inverter. Control of the current wave shape is limited by the switching frequency of the inverter and by the available driving voltage across the interface reactor. The driving voltage across the interface reactor determines the maximum *di/dt* that can be achieved by the power filter. This is important because relatively high values of *di/dt* may be needed to cancel higher order harmonic components.

The voltage source inverter is the heart of the active power filter. In the system model of the project it has been modelled as a three phase ,full wave inverter (IGBT based). Each of the three identical inverter legs consisted of two IGBT and two anti-parallel diodes. The igbt used here is modelled in the simulink as a resistor (R_{on}) and inductor(L_{on}) in series with a switch(transistor) controlled by a logical signal. It switches between on and off state instantaneously when triggered.

6.9 INTERFACE REACTOR

The interface reactor provides the isolation and filtering between the output of the voltage source inverter and the power system where the active power filter is connected. The inductance allows the output of the active power filter to look like a current source to the power system. The inductance makes it possible to charge the dc capacitor to a voltage greater than the ac line-to-line peak voltage. The inductance also functions like a commutation impedance. It limits the magnitude of a current spike during commutation and prevents the switching device from seeing an excessive rate of current change. Besides these, it is not possible to connect a sinusoidal voltage supply to the non-sinusoidal output of the voltage source inverter without a reactor. Sizing of the reactor value must take into account control of the inverter switching frequencies and the characteristics of the nonlinear load to be compensated.

6.10 REFERENCE CURRENT GENERATION

In this shunt active power filter, control is accomplished by monitoring the three phase line currents to the nonlinear load and the three phase line-to-neutral voltages at the load bus, and then generating the three phase reference currents that should be supplied by the voltage source inverter. In this simulation study compensating current reference signal is derived from the measured quantities by the use of the Instantaneous Reactive Power Theory based method. The general definitions of active and reactive power have been presented in references [Akagi et al., 1984, Akagi et al., 1986]. In this formulation, active and reactive powers are expressed as the dot and cross product of voltage and current vectors. Once the compensating currents are detected, they are used as a reference signal in the inverter current control loop and thus compared with the real voltage source inverter current to generate the switching control signals. To deal with instantaneous voltages and currents in three-phase circuits mathematically, it is adequate to express their quantities as the instantaneous space vectors. For simplicity the three phase voltages and currents excluding zero-phase sequence components will be considered i.e. three phase 3 wire systems.

In *a*, *b*, *c* coordinates, the *a*, *b* and *c* axes are fixed on the same plane, apart from each other by $2\pi/3$. The instantaneous space vectors $\mathbf{e}_{\alpha}$ and $\mathbf{i}_{\alpha}$ are set on the α- axis and their amplitude and direction vary with the passage of time. These space vectors are easily transformed into α,β coordinates as follows:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad \text{(i)}$$

$$\begin{bmatrix} \mathrm{i}_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad \text{(ii)}$$

Where the α and β axes are the orthogonal coordinates. Necessarily, e_α and i_α are on the α axis and e_β and i_β are on the β axis. Their amplitude and direction vary with the passage of time.

The conventional instantaneous power on the three-phase circuit can be defined as follows:

$$\boldsymbol{p} = e_\alpha \times i_\alpha + e_\beta \times i_\beta = v_a i_a + v_b i_b + v_c i_c\ . \qquad \text{(iii)}$$

In order to define instantaneous reactive power, the instantaneous imaginary power space vector is defined as follows:

$$\boldsymbol{q} = e_\alpha \times i_\beta + e_\beta \times i_\alpha \qquad \text{(iv)}$$

This space vector is the imaginary axis vector and is perpendicular to the real plane on the α,β coordinates, to be in compliance with the right hand rule. Taking into consideration that e_α is parallel to i_α and e_β to i_β, the conventional instantaneous power p and the instantaneous imaginary power q , are expressed by

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad \text{(v)}$$

By using the theory explained above, the transformation of the three-phase bus voltages v_a ,v_b ,v_c and the three-phase nonlinear load currents i_{La} , i_{Lb} , i_{Lc} into the α-β orthogonal coordinates gives the following expressions:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad \text{(vi)}$$

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad \text{(vii)}$$

The instantaneous real power p_L and the instantaneous imaginary power q_L on the load side can be defined as:

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \qquad \text{(viii)}$$

Equation (viii) is changed to

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_L \\ q_L \end{bmatrix} \qquad \text{(ix)}$$

The determinant with respect to e_α and e_β in eq.(ix) is not zero.

$\overline{P_l}$ and $\widetilde{P_l}$ are the dc and ac components of P_l .Likewise, $\overline{q_L}$ and $\widetilde{q_L}$ are the dc and ac components of q_L , respectively. Then the following relation exists:

$$p_L = \bar{p}_L + \tilde{p}_L \quad , \qquad q_L = \bar{q}_L + \tilde{q}_L \qquad \text{(x)}$$

From equation (ix), the α- phase load current i_{La} is divided into the following components:

$$i_{L\alpha} = \frac{e_\alpha}{e_\alpha{}^2 + e_\beta{}^2}\bar{p}_L + \frac{-e_\beta}{e_\alpha{}^2 + e_\beta{}^2}\bar{q}_L + \frac{e_\alpha}{e_\alpha{}^2 + e_\beta{}^2}\tilde{p}_L + \frac{-e_\beta}{e_\alpha{}^2 + e_\beta{}^2}\tilde{q}_L \qquad \text{(xi)}$$

The first term of the right hand-side of (xi) is the instantaneous value of the conventional fundamental active current. The second term is the instantaneous value of the conventional fundamental reactive current. The third term is the instantaneous value of the harmonic currents which represents the ac component of the instantaneous real power. The fourth term is the instantaneous value of the harmonic

currents which represents the ac component of the instantaneous imaginary power. From (xi) it is seen that the active power filter should compensate second, third and fourth terms to compensate for the harmonics and the reactive power. Figure 6.10 shows a basic compensation scheme of the instantaneous reactive power and harmonic currents. From the scheme it is seen that the active power filter supplies the

reactive power and harmonic real power so that only real power at fundamental frequency is drawn from the mains.

In the calculation circuit of the compensating reference currents, the following expression results:

$$\begin{bmatrix} i_{refa} \\ i_{refb} \\ i_{refc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p^* + p_{av} \\ q^* \end{bmatrix} \qquad \text{(xii)}$$

where p_{av} is the instantaneous real power corresponding to the loss of the active power filter, and p^* and q^* are given by

$$p^* = -\tilde{p}_L \quad , \qquad q^* = -q_L \qquad \text{(xiii)}$$

Figure 6.10 shows the calculation circuit of p^*.This basically consists of a high-pass filter configuration using a Butterworth low-pass filter. So, this circuit outputs $\widetilde{p_L}$ from p_L .The design of the low-pass filter is the most important in the control circuit, because various compensation characteristics are obtained in accordance with the cut off frequency and order of the low-pass filter.

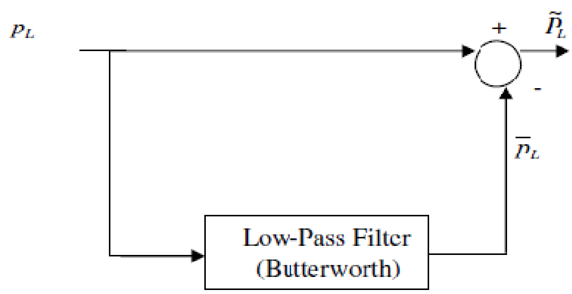


fig.6.10(a) calculation of p^*

The DC bus voltage V_{DC} of the voltage source inverter cannot be kept constant, owing to the power loss of the inverter circuit as no suitable DC voltage control circuit is used. This problem can be solved by controlling the magnitude of mains current.

A PI controller is used to control the DC capacitor voltage. Its transfer function can be represented as:

$$H(s) = K_p + K_I/(s)$$

Where, K_P is the proportion constant that determines the dynamic response of the DC bus voltage and K_I is the integration constant that determines its settling time.

The DC bus voltage is controlled by trimming the instantaneous real power p_{av}, which corresponds to the loss of the active power filter, while the instantaneous imaginary power does not have any effect on the DC capacitor voltage. The control circuit has the negative feedback loop to trim p_{av} automatically. The actual DC bus voltage value is fed back and compared with the desired DC bus voltage value. The difference is fed to a PID controller whose output is p_{av} . p_{av} is added to p^* and p_{av} adds a positive or negative DC value to p^* which corresponds to an active current at fundamental frequency. So the active line current at fundamental frequency flows into or out of the DC capacitor to regulate the DC voltage.

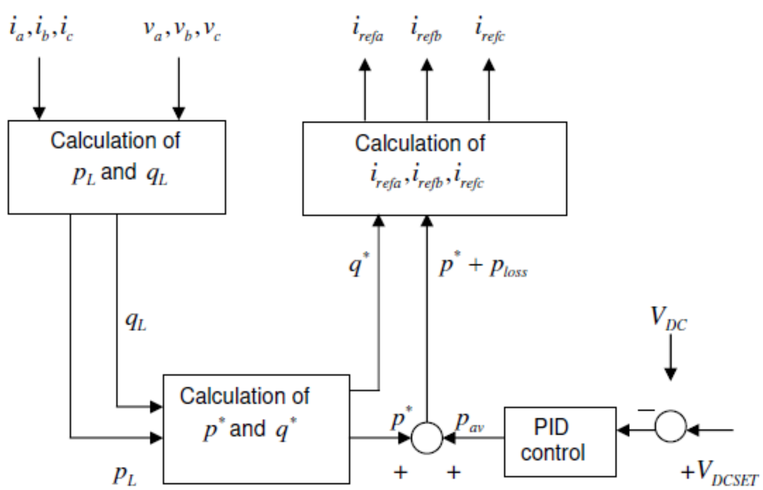
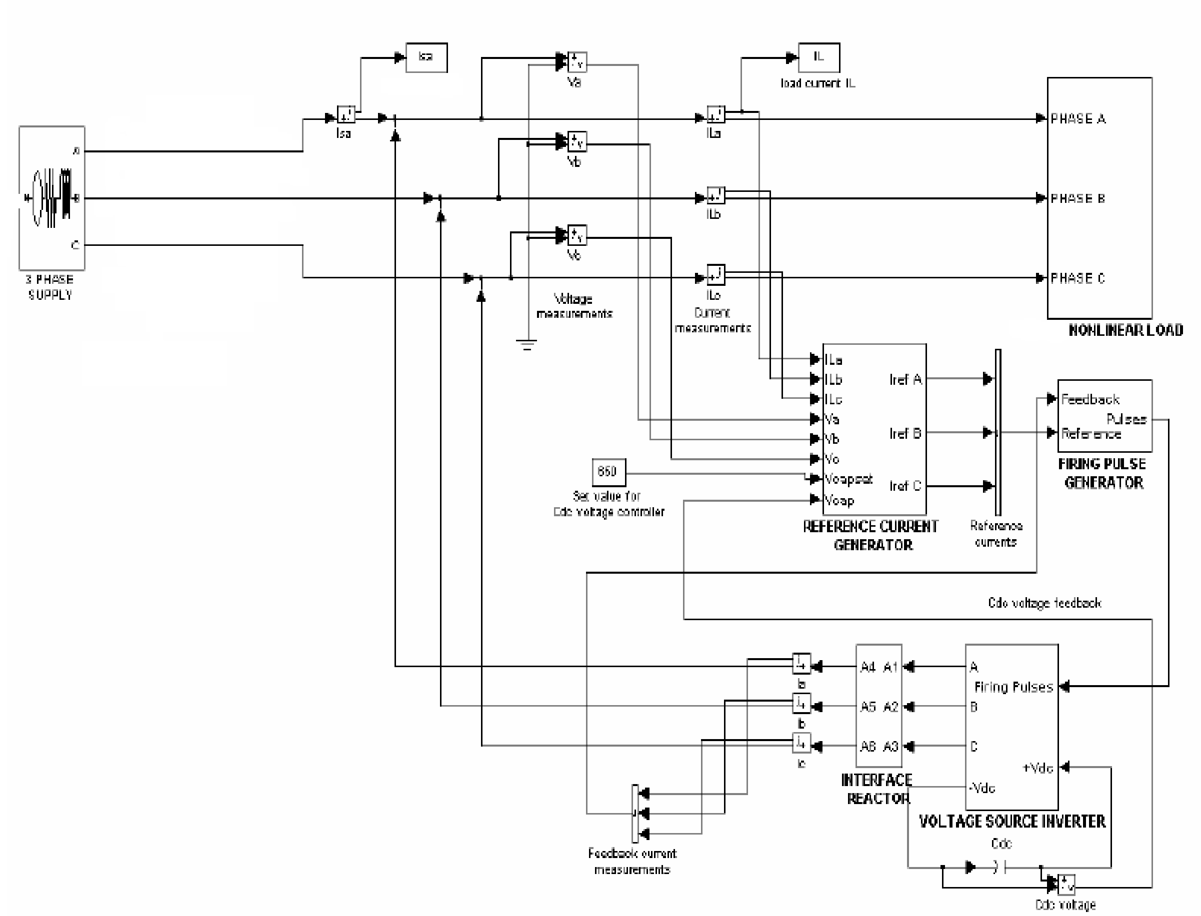


Fig. 6.10(b) Block diagram for reference current generator .

The matlab/simulink model of the 3-phase 3 –wire system is shown below :



6.11 CURRENT CONTROLLER

In the synthesis of the compensating currents , the kind of current control employed is of immense importance. It regulates the phase and amplitude of the output signals from the active filter. In our project ,two kinds of current control methods have been used, namely, hysteresis controller and Ramp comparison controller(constant frequency).

Hysteresis controller

In the hysteresis control technique the error function is centred in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit the hysteresis controller makes an appropriate switching decision to control the error within the preset band. However, variable switching frequency and high ripple content are the main disadvantages of hysteresis current control. It can be realized with high accuracy and fast response. The simulink model for hysteresis current controller is shown below .

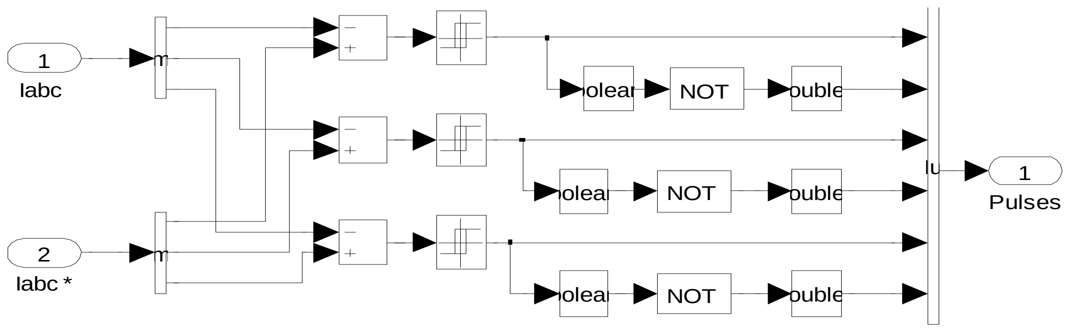


Fig. 6.11(a) hysteresis current controller

Ramp comparison controller

The controller can be thought of as producing sine-triangle PWM with the current error considered to be the modulating function. The current error is compared to a triangle waveform and if the current error is greater(less) than the triangle waveform, then the inverter leg is switched in the positive (negative) direction. With sine-triangle PWM , the inverter switches at the frequency of the triangle wave and produces well defined harmonics. Multiple crossings of the ramp by the current error may become a problem when the time rate change of the current error becomes greater than that of the ramp. However, such problems can be adjusted by changing the amplitude of the triangle wave suitably.

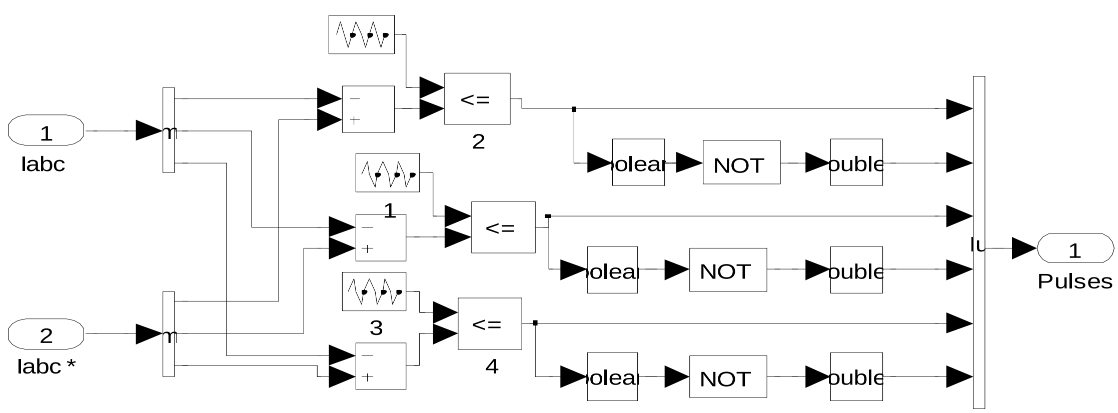


Fig.6.11(b) ramp comparison controller

6.12 SIMULATION RESULTS

I. Fig.6.12(a) shows the voltage , current waveforms of a load fed by 3-phase thyristor converter (at firing angle 45□). The source current Isa is also shown. The effect of non-linear loads is clearly observed.

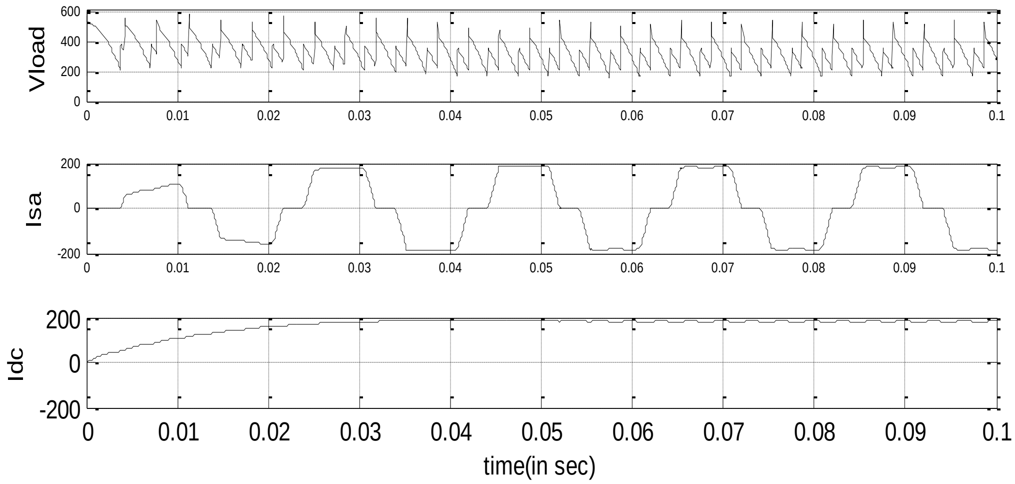


Fig.6.12(a) source voltage, current and dc load current waveforms for thyristor converters.

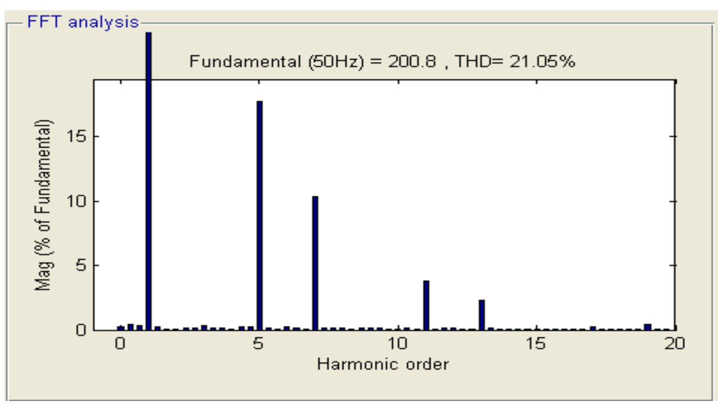
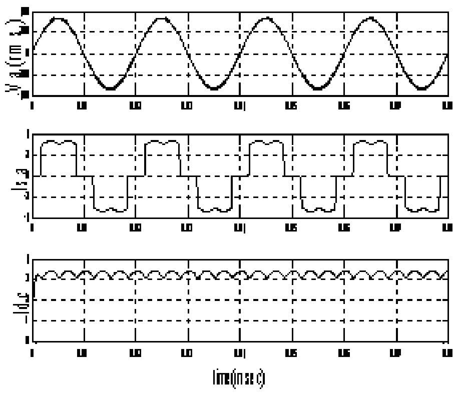


Fig6.12(b) THD of source current for three phase thyristor converter as non-linear load.

II. Fig.6.122(c) shows the current and voltage waveforms & the THD level of source current in a 6-pulse diode rectifier.



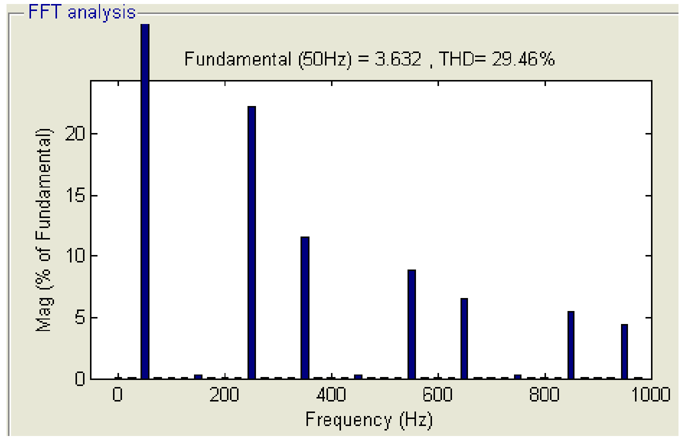
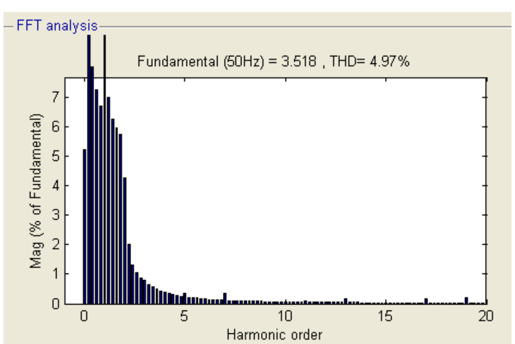
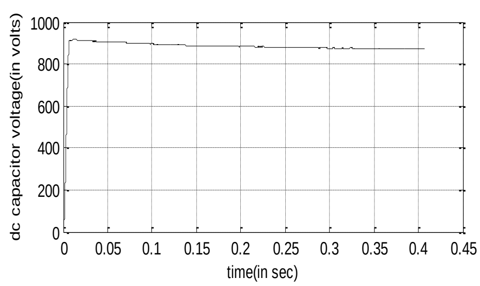


Fig.6.122(c)source voltage, current and pulsating load current waveforms.

Fig.6.122(c) THD of source current Isa.

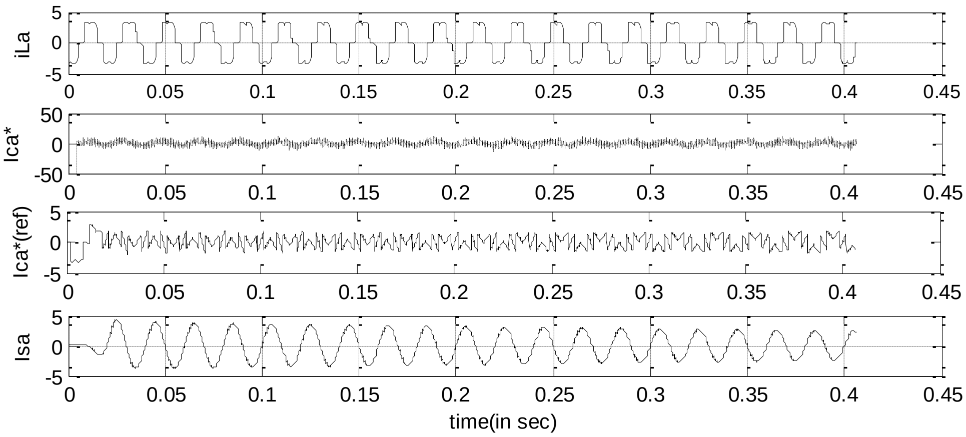
III. Fig.6.123(d) shows the source current ,load current ,compensating signal and reference compensating signal(Ica*,ref) waveforms. The DC capacitor voltage waveform of the shunt active filter and the THD level of source current after compensation. The control strategy employed is p-q theory , while hysteresis current controller has been implemented in this case.





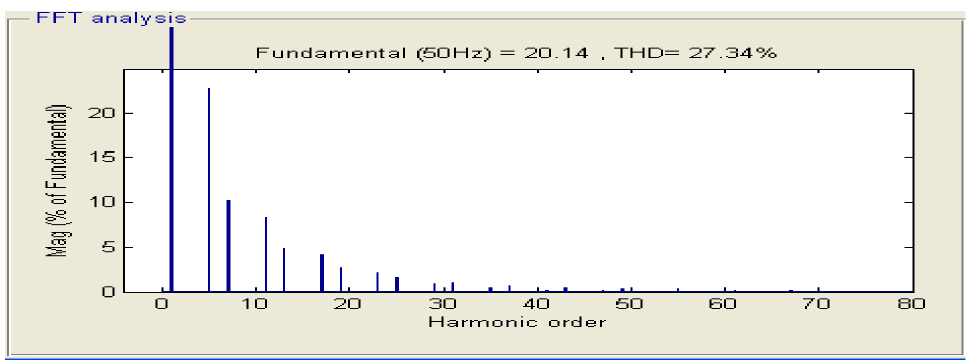
(i)THD level of source current after compensation.

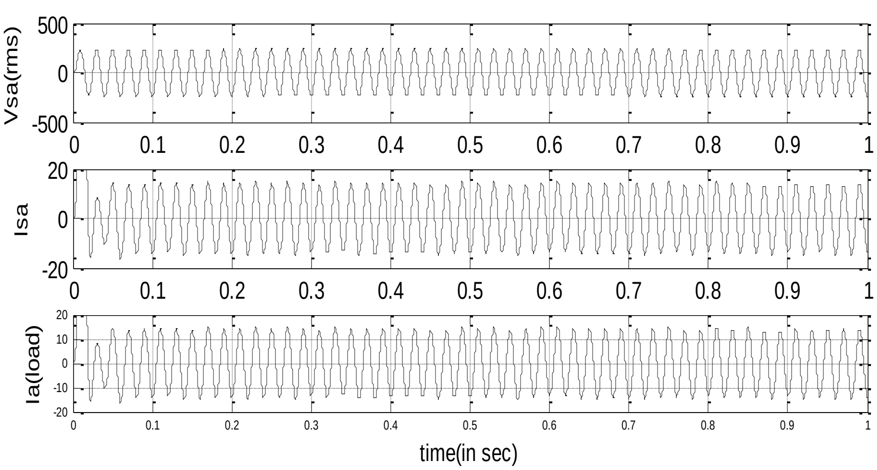
(ii)dc capacitor voltage



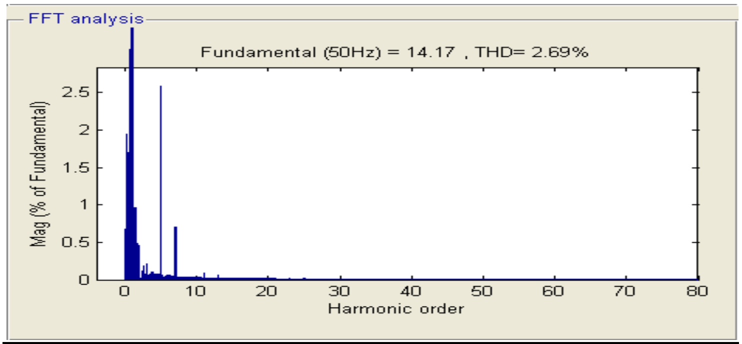
(iii) various current waveforms (source,load,reference and compensating currents)

(**iv**)fig.6.124(a,b,c,d) shows the source voltage/current ,load current waveforms after shunt active filtering. The THD level of source current before and after compensation are also shown in the FFT analysis. The shunt active filter makes use of pq theory for calculation of compensating signals. Constant frequency pwm current control has been employed here .

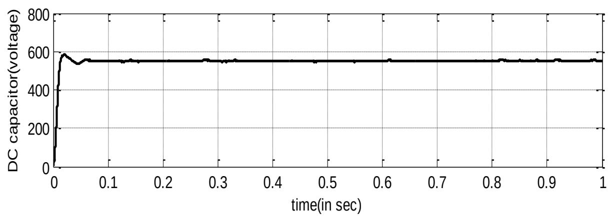




After compensation , THD levels of source current



DC capacitor voltage waveform



System parameters :

Supply voltage (line to ground voltage) - 415V

Supply frequency - 50Hz ; VSI switching frequency (constant PWM) – 10KHz

Coupling inductor – 3mH

DC side capacitor - 1000µF ; $V_{dc,ref.}$ = 650 V

Active load power – 1KW

Non-linear load – 6 pulse diode rectifier (21% THD)

Reactive load power – 1KVA

MULTILEVEL INVERTERS

7.1 INTRODUCTION

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells can be easily interfaced to a multilevel converter system for a high power application.

The concept of multilevel converters has been introduced since 1975. The term multilevel began with the three-level converter. Subsequently, several multilevel converter topologies have been developed. However, the elementary concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. The commutation of the power switches aggregate these multiple dc sources in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected.

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as follows.

- Staircase waveform quality: Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses; therefore electromagnetic compatibility (EMC) problems can be reduced.
- Common-mode (CM) voltage: Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced. Furthermore, CM voltage can be eliminated by using advanced modulation strategies such as that proposed in .
- Input current: Multilevel converters can draw input current with low distortion.
- Switching frequency: Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.

Unfortunately, multilevel converters do have some disadvantages. One particular disadvantage is the greater number of power semiconductor switches needed. Although lower voltage rated switches can be utilized in a multilevel converter, each switch requires a related gate drive circuit. This may cause the overall system to be more expensive and complex.

Plentiful multilevel converter topologies have been proposed during the last two decades. Contemporary research has engaged novel converter topologies and unique modulation schemes. Moreover, three different major multilevel converter structures have been reported in the literature: cascaded H-bridges converter with separate dc sources, diode clamped (neutral-clamped), and flying capacitors (capacitor clamped). Moreover, abundant modulation techniques and control paradigms have been developed for multilevel converters such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), space vector modulation (SVM), and others. In addition, many multilevel converter applications focus on industrial medium-voltage motor drives , utility interface for renewable energy systems , flexible AC transmission system (FACTS) , and traction drive systems .

7.2 DIFFERENT STRUCTURES OF MULTILEVEL INVERTERS

There are roughly three main types of transformer-less inverter topologies , which have been studied and received considerable interest from high power inverter system manufacturers : the flying capacitor inverter , diode clamped inverter and the cascaded H-bridge inverter. All share the same property, which is that the output filter can be dramatically reduced, and the usual bandwidth limit induced by the switching frequency can be reconsidered.

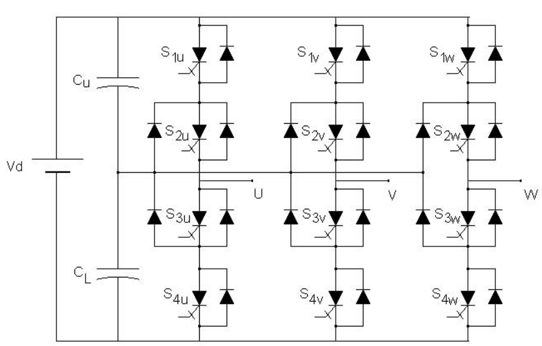


Fig.7.2 (a)

Schematic diagram of three level inverter

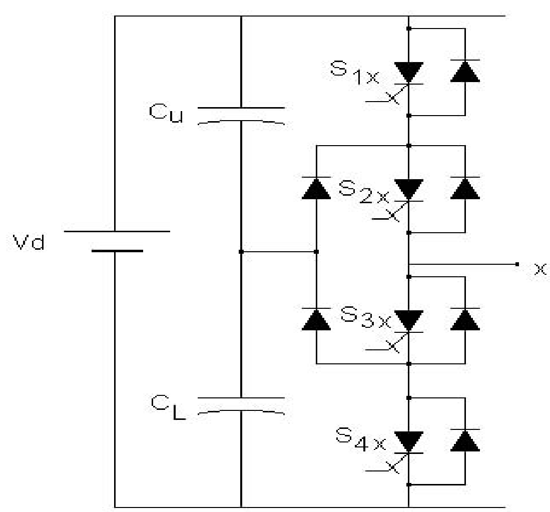


Fig 7.2(b)

one leg of the 3-level inverter

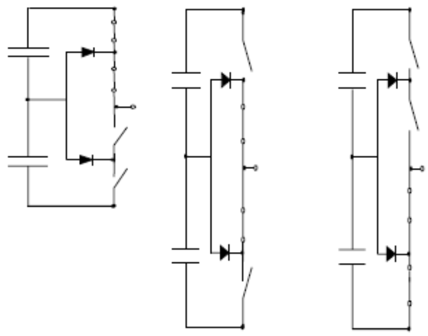


fig7.2 (c) switching states for a leg of the inverter

Output voltage Vao	S1x	S2x	S3x	S4x
Vdc	1	1	0	0
Vdc/2	0	1	1	0
0	0	0	1	1

S1x, S2x, S3x and S4x are the switches of one leg of the inverter. ‘1’ denotes on state and ‘0’ denotes off state .

7.3 MULTILEVEL INVERTERS WITH TRANSFORMERS

An inverter with M levels that has P = 6M pulses is obtained from an inverter with six pulses at the fundamental thanks to the following operating structure. We operate the inverters through a common dc source with successive phase displacement of 2p=6M.

The transformer secondary windings have appropriate configurations and connections to obtain the three-phase voltage by connecting the primary winding of the transformer in series and parallel, which displaces each waveform of the output voltage likewise obtained. Figure 7.3 shows a model with N pulses used as reactive power generator (SVG) made of eight (8) inverters with six (6) pulses using the transformers with particular connection so to eliminate harmonics and reduce the total harmonic distortion. This first type of multilevel inverter presents the following drawbacks:

1. Total pricing of the system is related mainly to the transformers used.
2. They produce roughly 50% of the total losses of the system.
3. They occupy 40% of the total surface allowed for the system.
4. They make the control difficult because of problems related to overvoltage caused by saturation in the transient state.

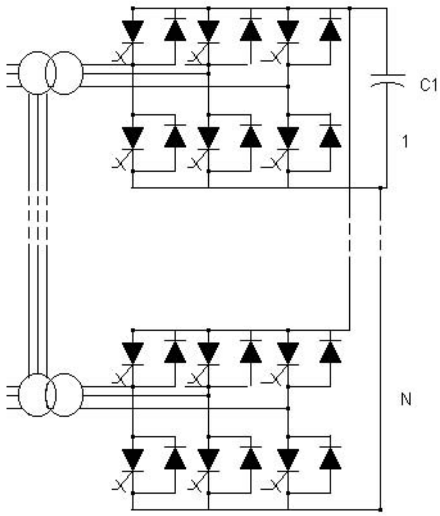


FIG.7.3 Schematic diagram of an inverter with 6 pulses by transformers

7.4 NEUTRAL POINT CLAMPED INVERTER

Figure 7.2a shows a schematic diagram of the structure of a three-level (Neutral-point clamped) inverter. It may be coupled directly to a level of voltage of 3.3 kV by using a GTO of 4.5 kV [26, 27]. Taking for reference one leg of the converter as shown in Fig. 7.2b, Table 7.2 gives overall switching states of the GTO, to obtain the voltages 0, E=2, and E three (3) states per leg; thus, for a three-phase converter there are 27 states in total. Figure 7.2(c) shows a structure of an M multilevel converter; in this case we use (M – 1)*2*3 GTO, (M-1)*2*3 diodes in anti-parallel, (M-1)*(M-2)* 3 clamping diodes, and (M-1) capacitors. Figure 7.4 represents the transitions of the switches of one leg according to the indicated states in Table 7.2. Figure 7.4 also shows the direction of the current flow for each state. (S11, S14); (S21, S24); (S31, S34) are the main switches; they are switched directly by control pulses. (S12, S13); (S22, S23); (S32, S33) are the auxiliary switches and allow connection of the output of each phase to neutral point (0). (D11–D32) intervene in this operation. As an example, for M = 51 for a direct connection with a 69-kV network, 300 GTOs and diodes in antiparallel, 50 capacitors, and 7350 clamping diodes are needed. This second type of converter presents the following advantages:

1. When M is very high, the distortion level is so low that the use of filters is unnecessary.
2. Constraints on the switches are low because the switching frequency may be lower than 500 Hz (there is a possibility of switching at the line frequency).
3. Reactive power flow can be controlled.

The main disadvantages are:

1. The number of diodes becomes excessively high with the increase in level.
2. It is more difficult to control the power flow of each converter.

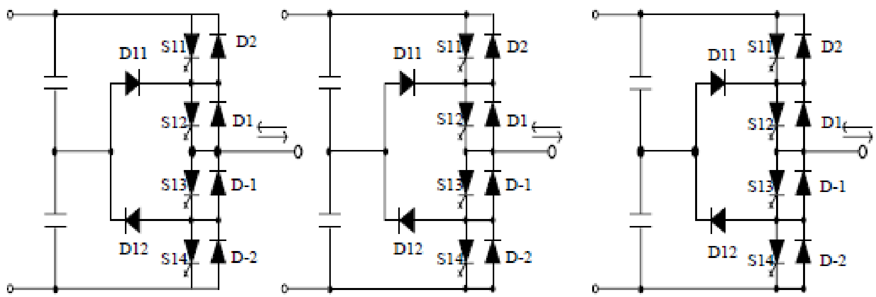


Fig 7.4 Current flow

7.5 FLYING CAPACITOR INVERTER

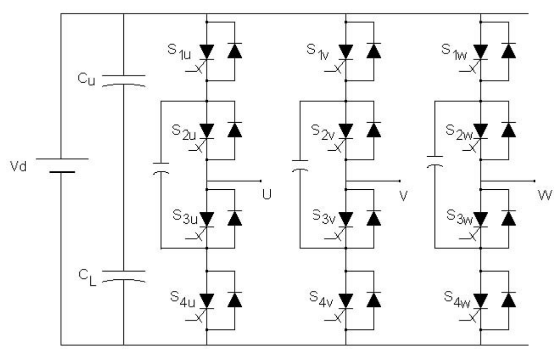


fig.7.5

Figure 7.5 shows the structure of a flying-capacitor type converter. We notice that compared to NPC-type converters a high number of auxiliary capacitors are needed, for M level (M-1) main capacitors and (M-1)*(M-2)/2 auxiliary capacitors. The main advantages of this type of converter are:

1. For a high M level, the use of a filter is unnecessary.
2. Control of active and reactive power flow is possible.

The drawbacks are:

1. The number of capacitors is very high.
2. Control of the system becomes difficult with the increase of M.

7.6 CASCADED TYPE MULTILEVEL INVERTER

This type of converter does not need any transformer clamping diodes, or flying capacitors; each bridge converter generates three levels of voltages (E; 0, and ÿE). For a three-phase configuration, the cascaded converters can be connected in star or delta. It has the following advantages:

1. It uses fewer components than the other types.
2. It has a simple control, since the converters present the same structure.

However, the main drawback is that it needs separate dc sources for the conversion of the active power, which limits its use.

7.7 SIMULATION RESULTS FOR 3-LEVEL INVERTERS (NEURTAL POINT CLAMPED TYPE)

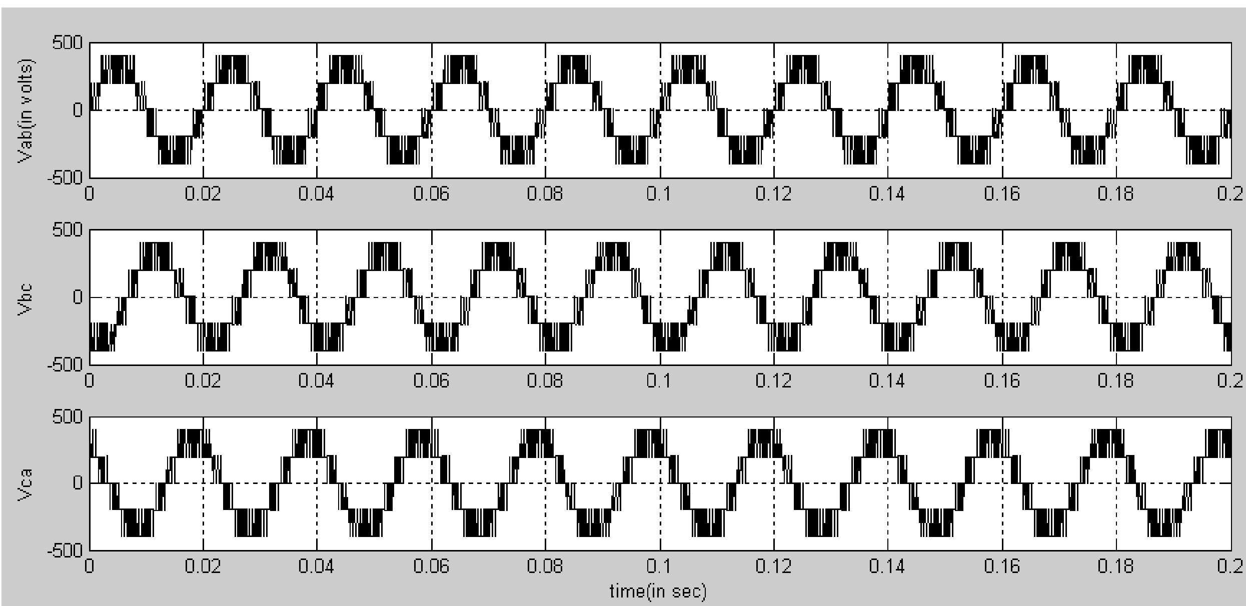


FIG. 7.7(a) LINE TO LINE VOLTAGES OF 3-LEVEL INVERTER

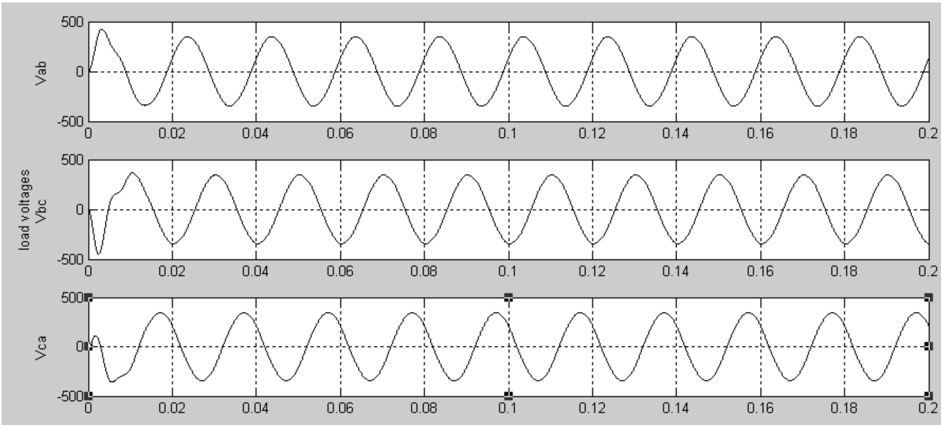


FIG7.7(b) load voltage waveforms .

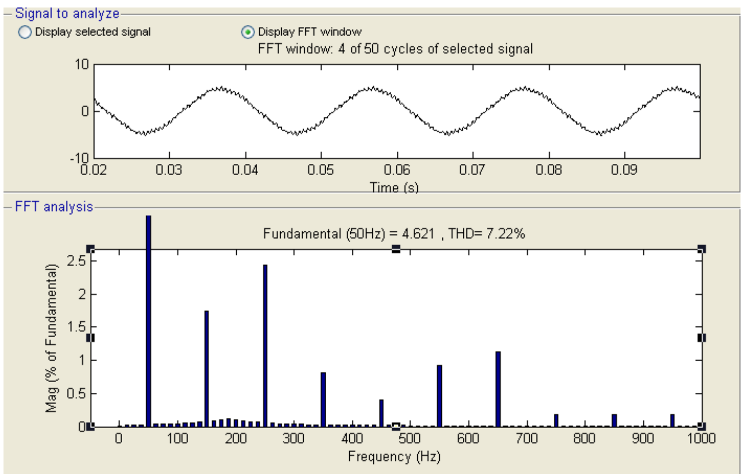


fig7.7(c)THD level of the output current.

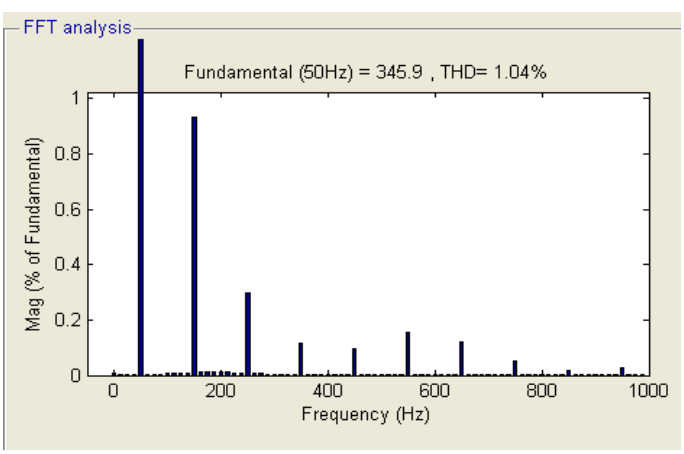


Fig 7.7 (d) THD level of line to line voltage of the multilevel inverter.

7.8 System parameters

Dc voltage = 200V

Output Frequency = 50Hz

Active load power = 1 KW

Reactive load power = 700 VAR

CONCLUSION

The shunt active power filter for three phase three wire system was modeled in MATLAB/SIMULINK and the simulations were carried out. The results achieved were satisfactory and within the permissible limits in accordance to IEEE standards.

Similarly , the simulations for three level inverters was performed and the stepped output voltages were obtained. Proper control strategies for switching of the multilevel inverters were used .Care must be taken while implementing the switching strategies for it is vital in the desired operation of the inverters .The harmonic distortions present in the load current and voltage waveforms were observed and calculated through FFT analysis tool in Matlab/simulink.

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